MOSES – Inflatable Causeway

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14. ABSTRACT
For decades, the United States Navy has used small displacement landing craft to be the conduit between heavy-tonnage ships offshore and the landing zone ashore. This has been the primary means of transporting troops and their combat and logistics support. The problem with this procedure is that displacement landing craft can only get close enough to the beach to disembark vehicles and personnel to wade the final distance ashore. Although the water is shallow, the vehicles must be specifically designed to operate in the corrosive seawater environment. An alternative method the Navy has used is to construct floating causeways. These systems have their own problems such as long deployment times and the inability to be used in Sea State 3 or higher. The goal of MOSES project is to design a causeway that can reach large ships in deep water, keep vehicles dry, and be safely operational in at least Sea State 4. Research of inflatable structures proved promising in that they are easily deployed, lightweight and compact making them extremely appealing. The biggest problem faced in the design was to make a rigid and stable structure using a flexible textile that can support any vehicle currently in use in today's Marine Expeditionary Brigade.

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Abstract

For decades, the United States Navy has used small displacement landing craft to be the connector between heavy-tonnage ships offshore and the landing zone ashore. This has been the primary means of transporting troops and their combat and logistics support. The problem with this procedure is that displacement landing craft disembark their cargo into the surf. Although the water is shallow, vehicles and cargo must be specifically designed to transit through the corrosive seawater environment.

An alternative method the Navy has used is to construct floating causeways. These systems have their own problems such as long deployment times and the inability to be used in Sea State 3 or higher. The goal of the MOSES project is to design a causeway that can reach large ships in deep water, keep vehicles dry, and be safely used in at least Sea State 4. Research of inflatable structures proved promising in that they are easily deployed, lightweight and compact making them extremely appealing. The biggest problem faced in the design was to make a rigid and stable structure using a flexible textile that can support any vehicle currently in use in today's Marine Expeditionary Brigade.

Acknowledgments

This report is the culmination of work conducted by students hired under the National Research Enterprise Intern Program sponsored by the Office of Naval Research. This program provides an opportunity for students to participate in research at a Department of Navy laboratory for 10 weeks during the summer. The goals of the program are to encourage participating students to pursue science and engineering careers, to further education via mentoring by laboratory personnel and their participation in research, and to make them aware of Navy research and technology efforts, which can lead to future employment.

At the Naval Surface Warfare Center Carderock Division, the single largest employer of summer interns is the Center for Innovation in Ship Design (CISD), which is part of the Ship Systems Integration and Design Department. The intern program is just one way in which CISD fulfils its role of conducting student outreach and developing ship designers.

The student team consisted of:

Kent Dickens

Philip Rosen

The team would like to acknowledge:

Dr. Colen Kennell who mentored this team as well as assisted us with his insight and vast experience towards the general design and configurations of MOSES;

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Executive Summary

MOSES was the name given to an inflatable causeway system designed to provide access from shallow draft vessels near the shore to the beach. The system is lightweight and easily deployable. MOSES is a large fabric structure filled with seawater and pressurized to become rigid. This causeway rests on the seafloor forming a roadway 1m above the surface of the sea.

Using the seafloor for support enables the causeway to remain stable in high sea states remaining relatively unaffected by large swells. The weight of the water in the fabric structure above sea level creates a large downward force, which holds the system in place. To minimize rolling, MOSES contains internal fabric ribs that run its entire length. These ribs create a structure with a flat bottom and top. This shape provides for a roadway on top and the flat bottom ensures stability against rolling.

MOSES must be pressurized to make the system rigid enough for vehicles to drive across. The required pressure is induced through the use of reservoirs that are open to the atmosphere. The reservoirs serve two main purposes. Firstly, they raise the level of the water above the roadway, which creates a sufficient pressure head to make the MOSES rigid. Secondly the reservoirs act as walls, deflecting the large swells expected in Sea State 4, which was a design requirement. A secondary benefit of the reservoirs is that they provide some allowance for punctures or tears in the fabric. The large reservoirs will enable the causeway to remain rigid for several minutes after a significant puncture allowing vehicles and personnel to safely evacuate MOSES.

Since the system needed to be easily deployed, a simple mechanism was designed to unroll the deflated causeway from the transport ship to the shore. Using fabric as the main structural component allows MOSES to be easily compacted and rolled around a giant spool. The recovery process is simply the reverse of the deployment process.

MOSES is a viable causeway concept that was demonstrated using a scale model test. The MOSES system is novel because of its fabric material construction, which can be compacted, stowed and easily deployed. Compared to the current causeways, MOSES has advantages in terms of deployment/recovery times, stowage volumes, and overall weight. These attributes make the inflatable causeway appealing for future development of this ship to shore transition technology.

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Nomenclature

SS	Sea State
NSWCCD	Naval Surface Warfare Center Carderock Division
CISD	Center for Innovation in Ship Design
MEB	Marine Expeditionary Brigade

Introduction

Objectives

The primary objective of this Innovation Cell was to develop a lightweight, rapidly deployable 'causeway' concept to enable movement of wheeled and tracked military vehicles from shallow draft ships through the surf zone to shore without wetting the vehicles. A system that meets these objectives would allow for the swift unloading of cargo and vehicles with minimal damage due to contact with seawater. A lightweight and compact system would also be very advantageous because space and weight are always at a premium on any naval vessel. Also current causeway structures require large crews and days to construct so a causeway design that could be erected in a few hours is very attractive.

While these were the primary objectives, there were other goals that would be worthwhile to attain. One goal was operability in at least Sea State 4 conditions. Operability under these conditions would greatly increase the time window in which the Navy could unload a Marine Expeditionary Brigade (MEB). Currently most deployment operations are limited to Sea State 2 conditions, which only occurs 1 out of every 5 days. Sea State 4 occurs 3 out of every 5 days, and it is easy to see the advantage of a system that is operable in Sea State 4. Additionally this system would need to be functional for all kinds of beach slopes, and also be able to reach a depth of at least 2m.

Table 1: Objectives

	Threshold	Goal
Operational Sea State	2	4
Water depth (m)	1	2
Beach gradient	30:1	50:1
Deployment time (hr)	6	2
Vehicle transfer speed (mph)	5	10
Stowage volume (cu m)	~80	~40
Useable life (# of deployments)	20	40
Useable life (yrs)	5	10

Design Evolutions

The first step was to determine the validity of the original concept envisioned.

Figure 1: MOSES Original Concept
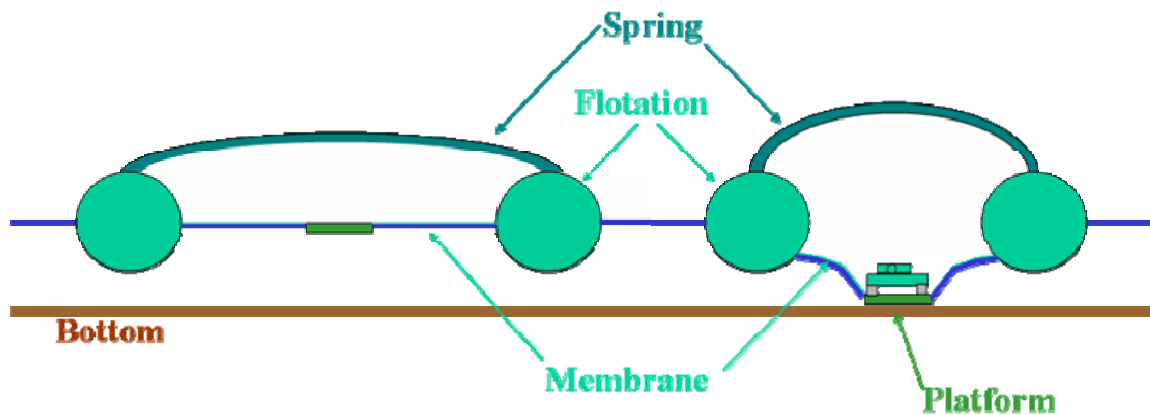
Figure 1 shows a cross sectional view of the original MOSES concept. The main structure of the system consists of four major parts. There are two large air filled pontoons, many transverse air beams, a watertight membrane, and a roadway platform. The theory behind the design is that when a heavy vehicle drives over the roadway it will sink to the seafloor. The seafloor would then provide the structural support for the roadway and also a steady surface on which to drive because the seafloor is stable regardless of the Sea State. The watertight membrane would be attached to the roadway and the pontoons creating a barrier that would keep the water out. The pontoons are very large and serve as a barrier to prevent swells from washing onto the roadway. The air beam arches hold the pontoons apart, which in turn keeps the membrane from collapsing onto the vehicle.

This is a very attractive idea but after some preliminary calculations it was found to be unreasonable. This was due to the fact that the idea would only be plausible for the heaviest vehicles in a MEB. Tanks would be able to use this system in depths less than five feet but lightweight vehicles such as a HMMWV could only use it in depths less than six inches. The shallow submergence depth for the HMMWV showed that this design idea is not an optimum solution. This concept however was not thrown out entirely as there were two elements of the concept that seemed to be very promising. The first was the idea of using inflatable fabric tubes as the main structural components. This idea is attractive because fabric tubes are very lightweight and easily compacted once deflated. The other idea was the use of the seafloor as the base of the MOSES system.

Evolution 1:

The first evolution used basically the same cross section as the original concept; however, the roadway would be fixed to the bottom by filling a compartment under the roadway with dredged sand. This weight would hold the roadway to the bottom and create a stable platform on which to drive. Also the entire system would be carried on a self-contained jack up barge. The major problem with this design is the large industrial process that would be required to set up the system. Also the barge would have to be carried to the

landing site, which would take up a lot of cargo room, and be very heavy. Another problem is that it would be nearly impossible to recover the entire system because of the approximately 1,000 tons of sand holding the roadway to the seafloor. Figures 2 and 3 illustrate this design evolution more clearly.

Figure 2: MOSES Evolution 1
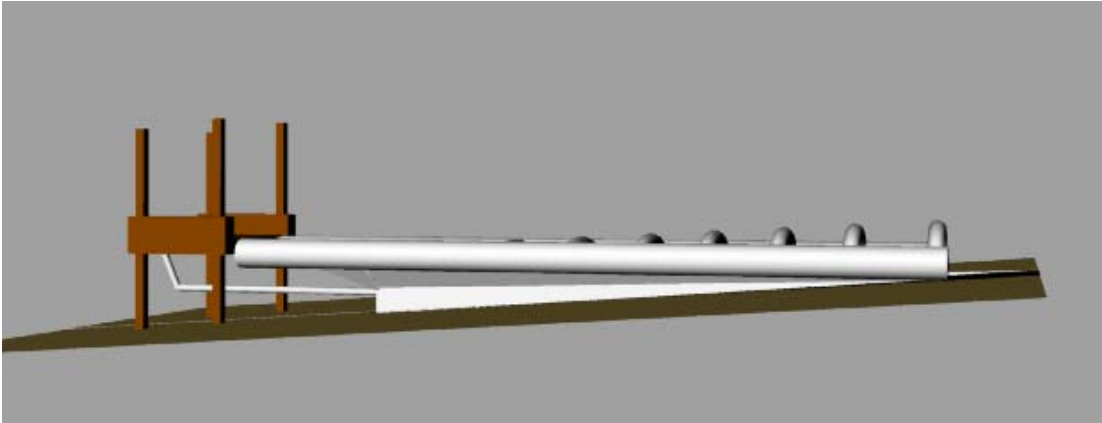
Figure 3: MOSES Evolution 1 (top view)
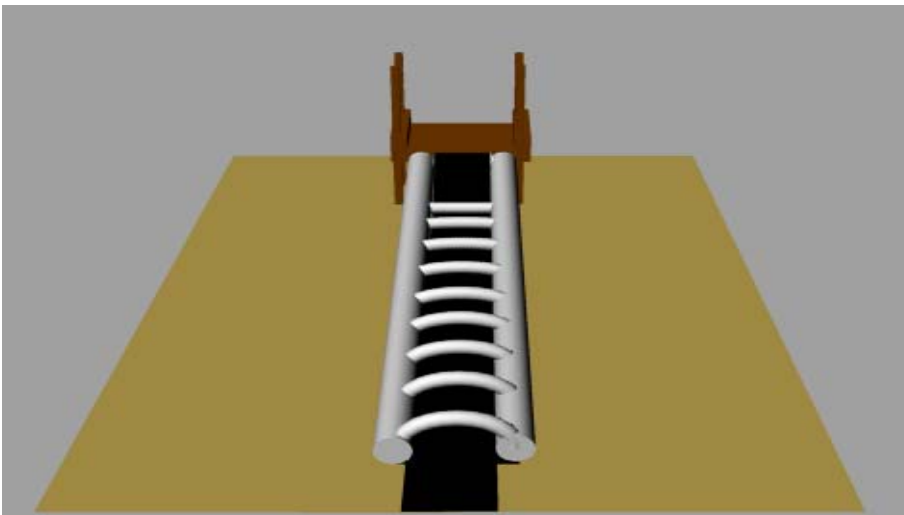
Evolution 2:

The second evolution is entirely different from the original concept and the first evolution. The concept behind this evolution was the use of one very large inflatable bag that rests on the sea floor and also elevates the roadway above the water surface. The bag will be pumped full of seawater which when pressurized will become extremely rigid due to incompressibility of seawater. The advantages of this idea are that it rests on the bottom making it stable in rough seas and there is only main structural element making the design extremely simple. The biggest draw back to this concept is there is no way to stop the flow of whitewater over the top of the bag. This is unfavorable because the goal of the project is to make a dry causeway. Also the whitewater could wash some of the

smaller vehicles into the water. Figure 4 illustrates the concept showing the system resting on the seafloor.

Figure 4: MOSES Evolution 2
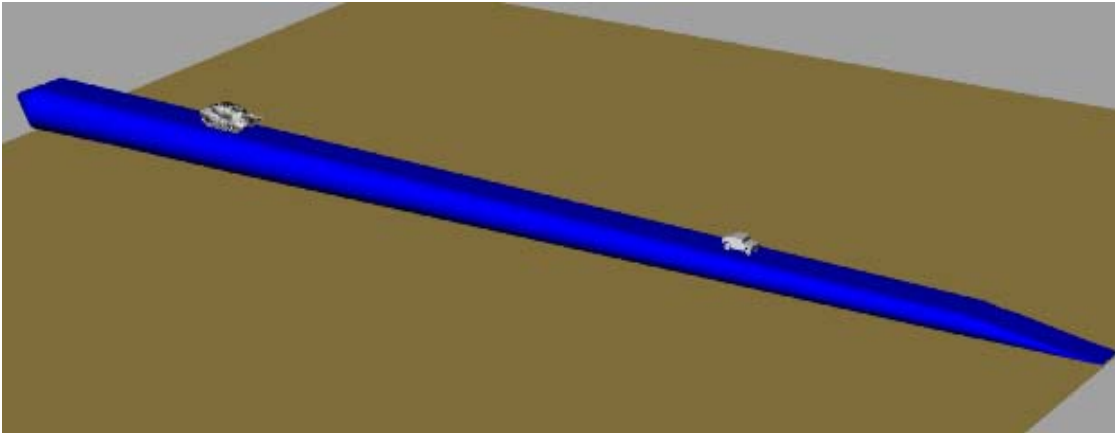
Evolution 3:

Evolution 3 is a modification of Evolution 2 attempting to mitigate the problems caused by whitewater. The idea behind this concept was to create pylon type structures to elevate the roadway and allow the whitewater to wash under the vehicles. This solves the problem of the whitewater but introduces its own problems. The roadway would have to be a structural element strong enough to support the weight of the heaviest vehicles in an MEB over spans measuring a couple of meters. This would require the use of strong roadway panels which would add weight as well as stowage volume to the system. Not only is the weight an issue but there would also be a rather laborious process in constructing the roadway since each roadway panel would have to be placed individually. This would drastically increase the time for deployment and recovery. Figures 5 and 6 illustrate some of the various aspects of Evolution 3.

Figure 5: MOSES Evolution 3
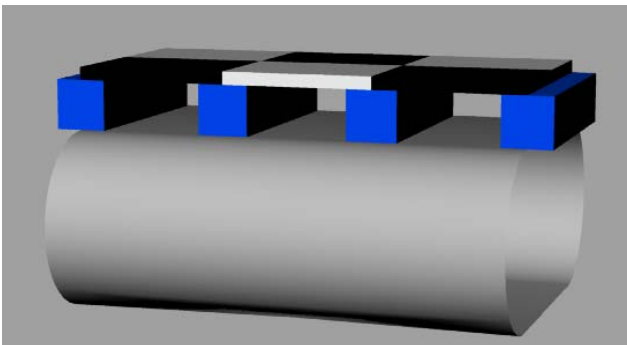
Figure 6: MOSES Evolution 3 variation
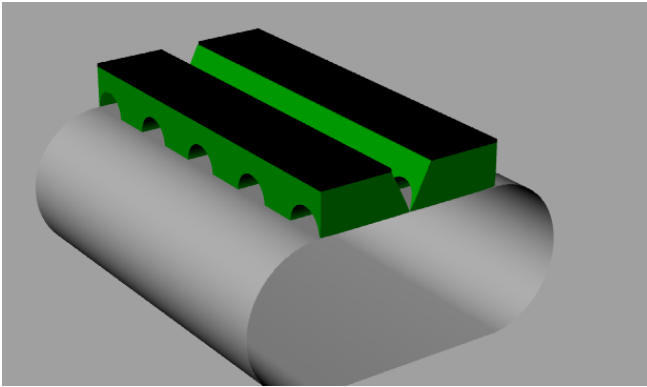
Final Design

The final design of MOSES combines the benefits from the previous three evolutions with several new ideas into a design of a lightweight and rapidly deployable causeway system. This design uses the simplicity of one main structural element which is a bag made from inelastic material pumped full of seawater. The system will extend from the ship to the shore up to a distance of at least 150m. The bag will be high enough for the bottom to rest on the seafloor up to a depth of 3m and the top/roadway to be elevated 1m above the surface of the water.

By filling the bag with seawater two things will be achieved. Due to the fact that water is incompressible and the fabric it is constructed from is very inelastic the system will become rigid when it is completely filled with seawater. This rigidity will allow vehicles to drive across it just like they would any other causeway. Also the water that is contained in the bag and above the waterline will provide a large anchoring force, which will keep MOSES firmly planted on the seafloor. Resting the MOSES on the seafloor is desired because it should be stable even in Sea State 4 since the system will behave independently of the swells. There is not just a stability problem in Sea State 4 but there is also the problem of whitewater washing across the roadway.

The whitewater will not be eliminated but rather mitigated through the use of two walls on either side of the roadway. These walls will be constructed by draping a watertight membrane over a structure of air beams. They will be 0.5m wide and will hold water. These walls will act as a reservoir and provide two benefits. The first benefit is that it will supply a pressure head in the main body of the bag. By keeping the water in the bag pressurized the body will remain rigid and stable. The second benefit is that the reservoir provides protection against leaks. It is important that MOSES not pop like a balloon but sufficient time for personnel and vehicles to evacuate safely.

The other main element of MOSES is the roadway. The roadway will be made of a very rugged and lightweight material. A planking system will be used as the structure for the roadway. The planks will be laid across the surface of the bag and each individual plank will be attached to the bag. This will allow for the entire system roadway bag and reservoir to be rolled at one time during deployment and recovery.

The Figures 7 and 8 illustrate the preferred design concept. Figure 7 shows an isometric view of the entire length of MOSES with a M1A1 tank placed on the roadway to give some idea of scale. Figure 8 is a magnified view of the reservoir system showing the framework of the air beams and the reservoir.

Figure 7: MOSES Final Design
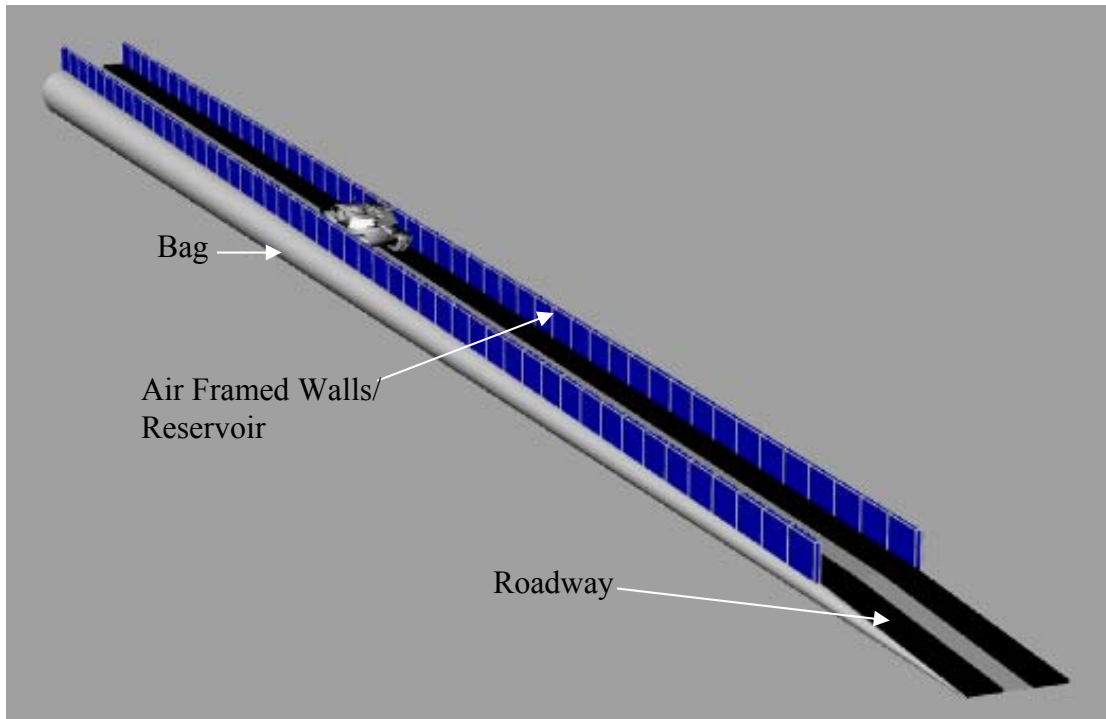
Figure 8: MOSES Final Design
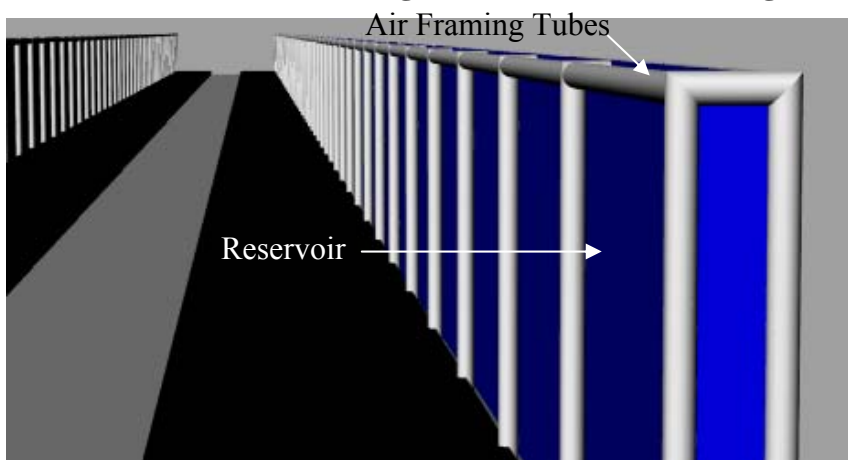
Design Details

Structural Details

The bag will be constructed in such a way that it will take an ovular shape. This shape is desired because it will give the MOSES a flat bottom and a flat roadway. The flat bottom will give the structure stability because it will not be able to roll on the seafloor. By making the roadway flat, vehicles will easily be able to drive across the MOSES. To create this shape, fabric ribs will be attached to the interior of the bag and run its entire length. These ribs will restrict the form and give the MOSES a flat top and bottom. In addition to using ribs the bag shape will also be modified with a taper. The taper will follow the beach slope, making the ship end taller than the beach end. The reason for the taper is to ensure that the roadway will remain 1m above the surface of the water. This means that the ship end of MOSES will be 4m tall and the beach end will be 1m tall. The taper also affects the width of the bag as it reduces from 9m at the ship end to 6m at the beach end.

Figure 9 shows a cross section of the ship end of the MOSES. This cross section is taken at the ship end and shows the overall configuration of the system. Figure 10 shows a profile view and how the bottom of MOSES is tapered while the roadway and reservoir remain at a constant height.

Figure 9: Cross Section View
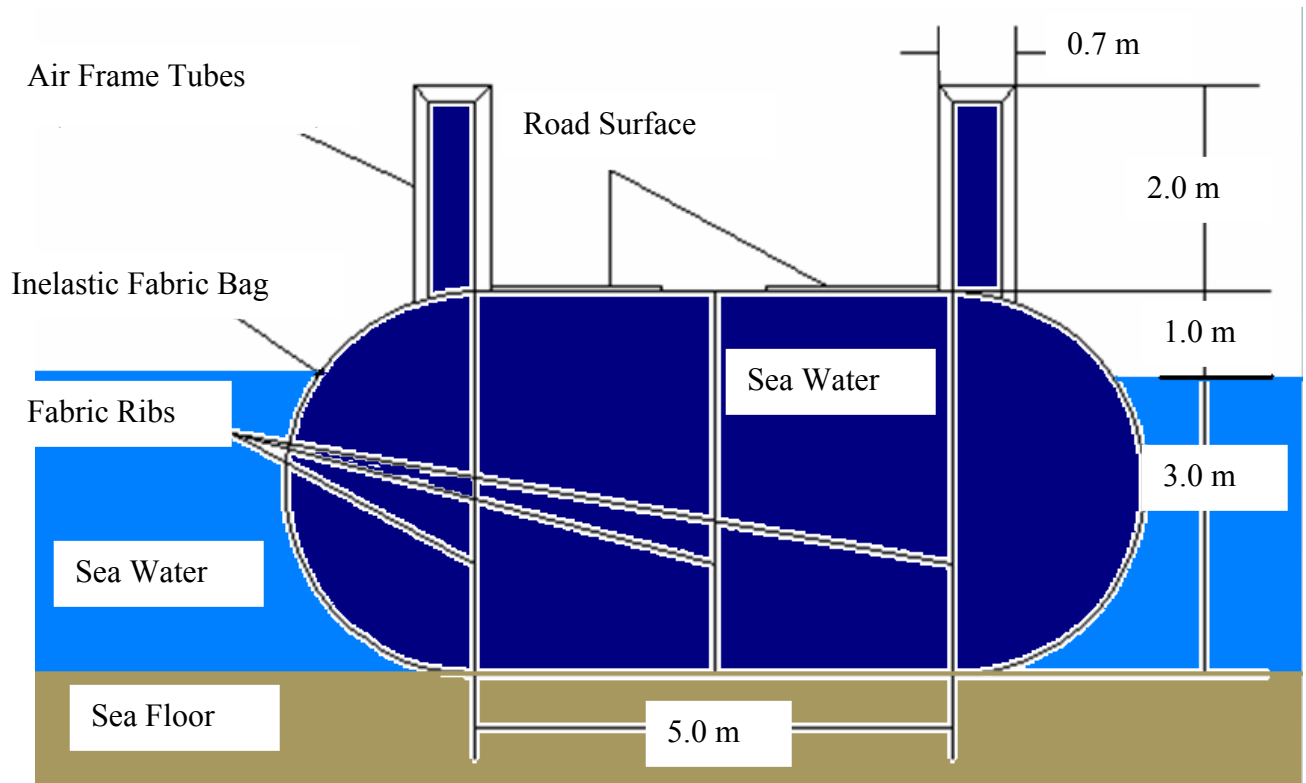
Figure 10: Profile View
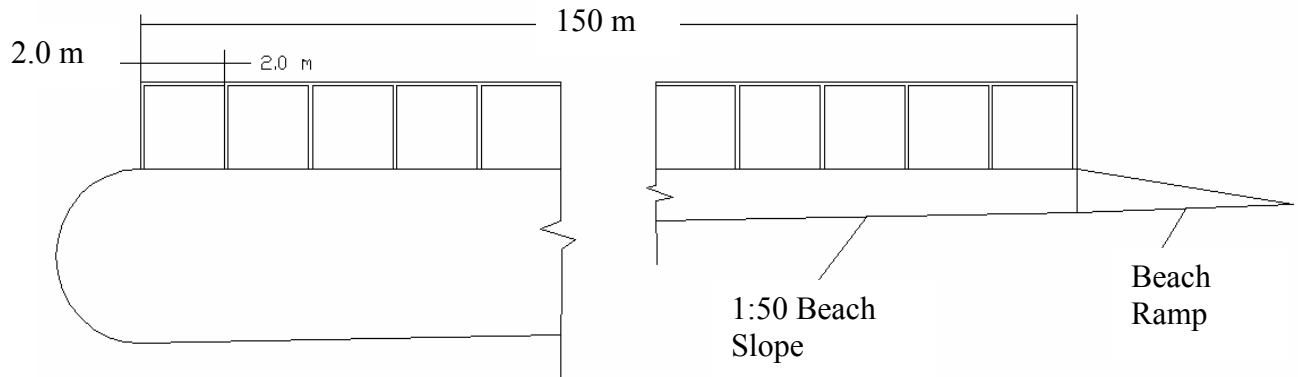
Unlike the main body of the bag the reservoir walls will have one single cross section. There will be one reservoir wall attached to each side of the bag and they will run the entire length of the structure. The walls will be 2m in height and 0.5m in width. The airframe supporting the reservoir will be constructed using fabric formed into 10cm diameter airtight tubes. When these tubes are inflated they will provide a structure strong enough to support the loads induced by a 3m swell.

The air framing will include three different types of tubes vertical, transverse and horizontal. The vertical tubes will extend from the bag in the vertical direction 2m. These tubes give the reservoir its height. The transverse tubes will connect the vertical tubes and will be 0.7m in length. These tubes will give the reservoir its width. The horizontal tubes run the length of MOSES and serve two purposes. They supply the entire airframe structure with air and they hold up the watertight membrane that will contain the water for the reservoir. The water in the reservoir will be allowed to drain freely into the body of the bag through a series of ports running the length of the reservoir.

Another structural component of the system is the roadway planking. These planks will be laid out in two tracks down the length of the main body. The tracks will be 2m wide and will have a 1m gap in between them. Each plank will be 200cm long, 4cm tall and 10cm wide. These planks will be laid transversely across the bag and will have a 2 cm space between each plank. This space is intended to provide drainage for any water that might splash onto the roadway. Also this spacing will allow the planking to be rolled around a spool for easy deployment and recovery. Figure 11 and 12 show details of the roadway.

Figure 11: Plan View
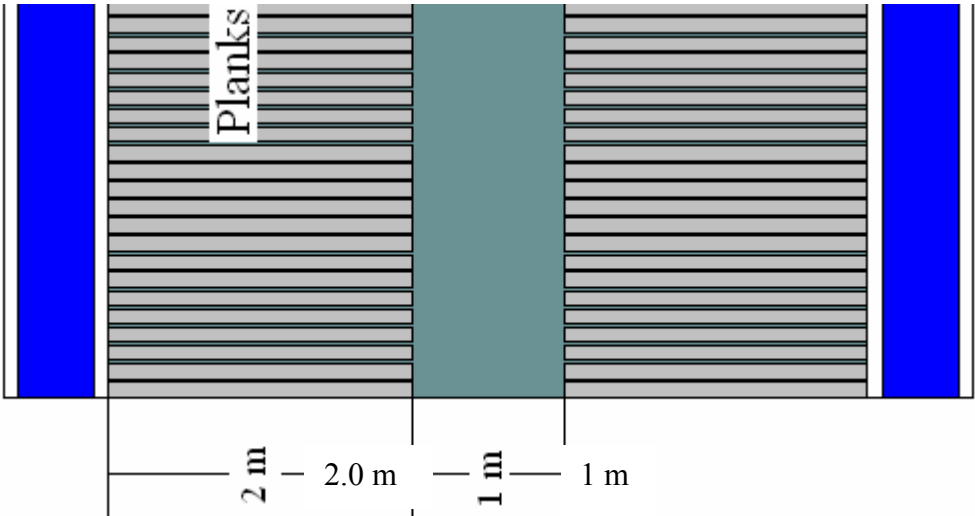
Figure 12: Roadway
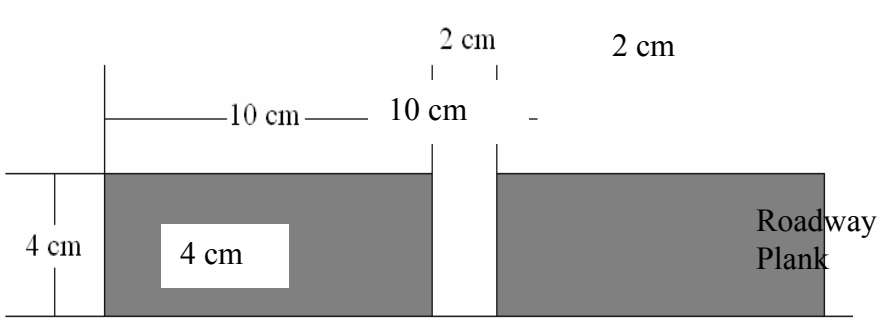
Structural Calculations

Internal Water Pressure

The MOSES system relies on seawater to provide the bag its strength and rigidity. Therefore the water pressure in the bag is extremely important in determining the feasibility of the concept. The water pressure drives the design because it imparts stresses on the bag and is a deciding factor for determining the height of the reservoir.

The pressure in the bag is found simply by using the equation, $P=\rho gh$. Where the pressure head is determined by taking the height from the sea level to the waterline in the reservoir. The minimum pressure is the pressure required to fully inflate the bag and elevate the roadway, causing the system to become a rigid body. The maximum pressure is the pressure induced when the reservoir is completely filled. The pressure head in the MOSES can never exceed 3m because the reservoirs are open at the top. Any excess water will simply spill over the sides instead of increasing the pressure. Using this model, the values in Table 2 were calculated. This table shows the pressure range expected for the maximum and minimum operational reservoir water levels. The pressures experienced by the bag are extremely small and the range between the maximum and minimum is only 18 kPa about 0.18 atm.

Table 2: Induced Water Pressure

	kPa	psi
Minimum Pressure	12.29	1.79
Maximum Pressure	30.61	4.45

It is possible to determine the highest pressure that the bag can experience but it is not as easy to determine a model for the effects that moving vehicles have on the internal bag pressure. When the weight of a tank is considered on its own it seems like a very large weight and that it would induce a large pressure in the bag. However, when the weight of the entire MOSES system above the waterline is compared to an M1A1, a tank seems very small. The disparity between the two weights leads to the conclusion that a 63 tonne tank will have a very slight effect on a 1500 tonne MOSES. The comparison between these values is shown in more detail in Table 3.

Table 3: Weight Comparisons

	Weight of 1 Tank	Weight of Water Above Water Line	Tank to Water Weight Ratio
Mton	63.64	1500	4.24%
	Weight of 1 Tank	Reservoir Weight	Tank to Reservoir Ratio
Mton	63.64	300	21.2%

Stress in the Fabric of the Bag

MOSES is a structure made from a flexible fabric, which poses a considerable challenge as far as structural analysis is concerned. Instead of using normal statics and stress

analysis other methods had to be sought. In order to gain a better understanding of how an internal pressure induces stress in a fabric tube shell theory was researched. Through this research it was found that in order to analyze an inflated structure with the same shape as MOSES it would take a detailed finite element analysis and more time than could be justified for such a preliminary design.

The area of hoop stress was also researched and yielded promising results. The solutions for hoop stress give the stresses in tubes with circular cross sections subjected to internal pressure. The equation for hoop stress is much simpler and because of this was used to model the stresses induced in the fabric. The equation for hoop stress is given below. Where σ is hoop stress, P is pressure, r is the radius of the vessel, and t is the thickness of the material used for the shell.

Equation 1: Hoop Stress

$$\sigma = \frac{P \bullet r}{t}$$

Table 4 shows the stresses that will be induced in the fabric under different loading combinations.

Table 4: Approximate Stress in Bag

	kPa	kPa	kPa	m	m	MPa
Number of tanks	Pressure increase	Over pressure	Total pressure	Thickness	Radius (take largest)	Stress
0	0.00	1.00	1.00	0.0009	4.50	5.00
1	0.55	1.00	1.55	0.0009	4.50	7.77
2	1.11	1.00	2.11	0.0009	4.50	10.54
3	1.66	1.00	2.66	0.0009	4.50	13.31
4	2.22	1.00	3.22	0.0009	4.50	16.08
5	2.77	1.00	3.77	0.0009	4.50	18.85
20	11.08	1.00	12.08	0.0009	4.50	60.40

Since the equation for hoop stress does not perfectly model the MOSES very conservative values were taken for the thickness of the material and radius of the bag. The material thickness was taken as 0.9 mm because that was the thinnest high strength fabric that was found. The thinnest number was taken because thickness is in the denominator of the hoop stress equation and the smaller the denominator the larger the stress. The radius was taken as 4.5 m because this is the longest distance from the centroid of a cross section of MOSES to the exterior fabric.

Reservoir Sizing

There are three factors taken into account when determining the dimensions for the reservoirs. The height dimension is determined by the height of seas that must be deflected and also by the amount of pressure head that must be supplied to the bag. The width dimension for the reservoir is determined by the needed volume of water to give protection against leaks.

The height of Sea State 4 swells are expected to reach 3m, with the crest of the wave being 1.5m above the water line. When waves roll into a reflective surface, like the side of MOSES, they can sometimes build to double their original height. In order to protect against this scenario, the walls were constructed to be shields reaching 3m above the water line. The walls will be elevated by the body of the bag to an elevation of 1m and will need to be 2m tall in order to protect against Sea State 4 swells.

Another parameter for sizing the height of the wall is the pressure head required in the bag. Further research is needed before a proper prediction can be made in regards to the induced pressures due to vehicular surface loadings. While these pressure changes cannot be determined the minimum allowable pressure head is known. The walls must be tall enough to supply the minimum pressure and also allow for enough of an increase in pressure to support the added loading of a tank. The minimum pressure head is 1.2m and the reservoirs allow for a head of 3m. This allows for a pressure head increase of 1.8m, which should be adequate to cope with the induced pressure of a tank driving down the roadway.

While the height of the reservoir can be increased to create a larger reservoir, the width is the primary dimension that most economically increases the reservoir volume. The width can be varied without adding structural supports because a wider reservoir does not require any extra strength in the airframe for support. A taller reservoir, on the other hand, would require a taller and stronger airframe, which would be more difficult to construct. In order to determine the necessary reservoir width Figure 13 was constructed showing the time that MOSES would take to deflate with a puncture of a given diameter.

Figure 13: Time to Deflate vs. Puncture Diameter

Time to Deflate Resevoir vs. Puncture Diameter
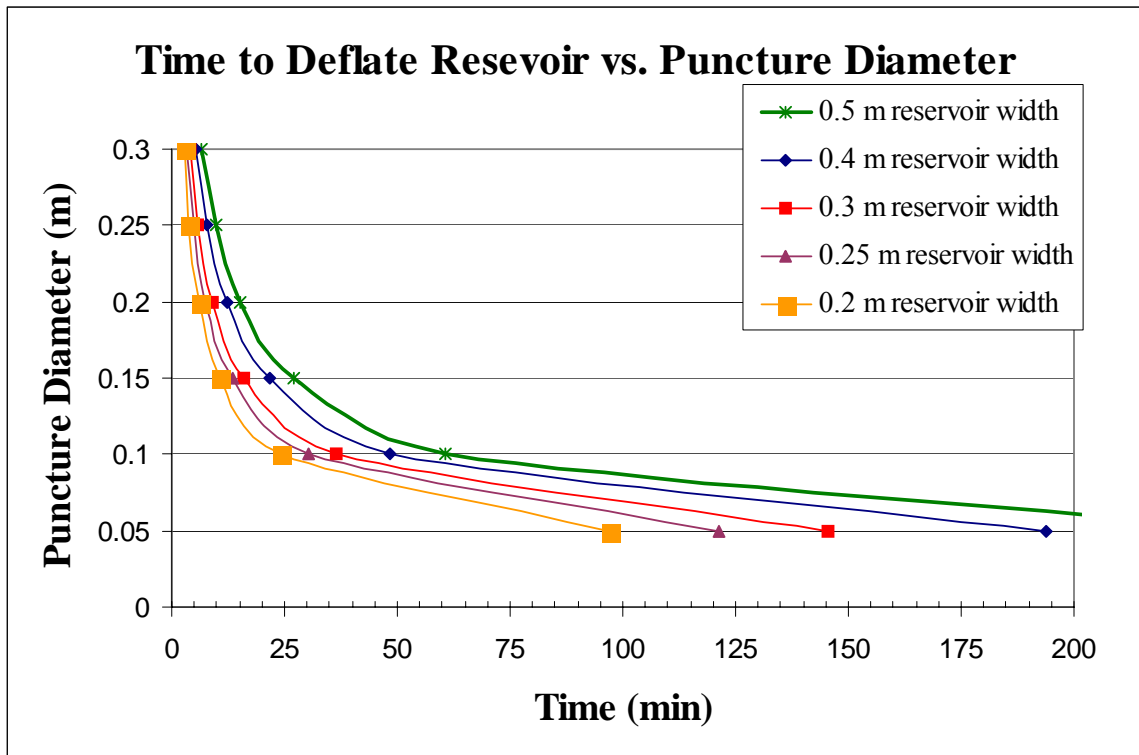
From Figure 13 it is easy to tell that with a small puncture, 5 cm in diameter, the 0.5m wide reservoir would take over 3 hours to drain. This would provide sufficient time to evacuate from MOSES and probably enough time to finish unloading an entire ship. For large punctures there is not that much of a disparity between the different sizes of reservoirs. For a puncture diameter of 30cm, the 0.2 m wide reservoir would provide a 2.7 minute window and the 0.5m wide reservoir a 6.7 minute window. The extra 4 minutes the 0.5m reservoir provides is very large when considering that it only takes 67 seconds for a vehicle traveling at 5 mph to cross MOSES.

The bag depressurizes very quickly when there is a large puncture but this should not be a problem because MOSES is not designed for use in a combat zone. The main puncture concerns are small tears from contact with the seafloor. The system's immense weight will be spread over a very large contact area and its ground pressure will only be 4 kPa (0.58 psi). This low contact pressure should greatly reduce the likelihood of large punctures and allow for the reservoirs to provide sufficient leak protection. The 0.5m wide reservoir was chosen because it provides large protection against leaks and does not take up too much room on the system. Also the 0.5m wide reservoir would allow for more ease in topping the system off through the use of the deployed ship's fire mains.

Airframe Calculations

From the dimensions of the reservoir, it is possible to determine the size and pressure required for the tubes needed for the airframe. The airframe must be strong enough to withstand the hydrostatic forces that will be created from the water in the reservoir and the waves breaking across the system. Pressurized air beams have been used as a structural member in many applications in the past including inflatable buildings and inflatable wings. From research on these two areas an equation was found that relate pressure of an air beam to the bending moment experienced by the beam.

$$ P = \frac{8M}{\pi d^3 \left(1 - \dfrac{2}{\tan^2 \beta} \right)} $$

Equation 2: Bending Moment

The parameters used to determine the pressure required in the air beam are d the diameter of the tube, M the moment that must be resisted, and Beta which is the bias angle of the braid. This equation is specific to a fabric that is braided and not woven. Figure 14 shows what the bias angle in a braided fabric.

Figure 14: Braid Angle
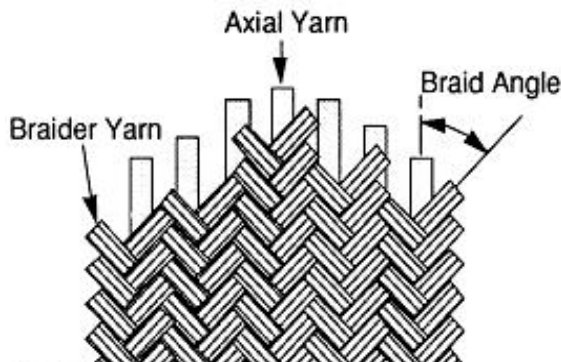
Because braided fabrics are stronger than woven for air beams, braided were chosen for use in the MOSES airframe. Three factors had to be taken into account when designing the airframe and these were the spacing of the vertical supports, the diameter of the tubes, and the air pressure required to create a structure strong enough to support the walls. The relationships between these factors for the vertical supports can be seen in Table 5.

Table 5: Vertical Tubes

Vertical Tubes							
m	m	m	kN	kN-m	degrees	kPa	MPa
Height of wall	Diameter of structural tubes	Spacing of vertical tubes	Hydrostatic force	Moment (hydrostatic pressure)	Bias angle	Air pressure (braid)	Stress (braid)
2	0.1	3	58.8	39.2	75	116.55	0.647
2	0.1	2	39.2	26.13	75	77.706	0.431
2	0.1	1	19.6	13.06	75	38.853	0.215
2	0.15	4	78.4	52.26	75	46.048	0.383
2	0.15	3	58.8	39.2	75	34.536	0.287
2	0.15	2	39.2	26.13	75	23.024	0.191

Bending moments were calculated by using the hydrostatic forces created by the 2m of water in the reservoir. The spacing of the vertical beams greatly affected the moment that each support would be required to resist and was iterated along with the diameter of the tube in order to see what pressures would be required for the different configurations.

Ten cm diameter tubes were selected with a spacing of 2m on center. Ten cm diameter tubes were chosen over 15cm tubes because the overall volume of air for the system decreased dramatically when 10 cm tubes are used. Also the pressure required by the 10cm tubes at 2m spacing is fairly low (0.77 atm) and can easily be supplied by many different types of air pumps.

The horizontal tubes also needed to be analyzed to determine their dimensions and required pressures. The horizontal tubes under went the same iterations as the vertical tubes. The values for these iterations are shown in Table 6.

Table 6: Horizontal Tubes

Horizontal Tubes							
m	m	m	kN/m	kN-m	degrees	kPa	MPa
Height of wall	Diameter structural tubes	Spacing between vertical tubes	Hydrostatic force	Moment (hydrostatic pressure)	Bias angle	Air pressure (braid)	Stress (braid)
2	0.1	3	4.9	5.51	75	16.39	0.091
2	0.1	2	4.9	2.45	75	7.28	0.040
2	0.1	1	4.9	0.61	75	1.82	0.010
2	0.15	4	4.9	9.8	75	8.63	0.071
2	0.15	3	4.9	5.51	75	4.85	0.040
2	0.15	2	4.9	2.45	75	2.15	0.017

Table 6 shows that the horizontal tubes are subjected to much smaller bending moments than the vertical tubes. The horizontal tubes could be made considerably smaller than the vertical tubes but for the simplicity of the air beam system both vertical and horizontal tubes will have the same diameter and air pressure.

The transverse tubes will experience no bending moments and are simply there to create the shape of the reservoir. For ease of construction, the transverse tubes have the same geometry and pressure as the other tubes.

Materials

Bag Material

Many bag materials were researched and decisions were based on strength of the material, elasticity, and strength retention in seawater. The strength of the material was considered secondary to elasticity because of a few points. The pressures that are induced in MOSES by the over pressure and loading are relatively small, so they exert low stresses. This would suggest researching materials with less strength, however the main theory that MOSES is based on is the fact that when pressurized it will become rigid. The material cannot have a lot of elasticity or it will stretch and not be able to sustain the design loads.

Table 7 shows a few of the materials of interest. The one chosen for its remarkable attributes is Supreme Protector (UHMW-PE-512WE). It is a brand new material and especially interesting because it is extremely strong, very little elongation and still positively buoyant. Kevlar and Zylon are good alternatives, but they are denser then water, hence they will not float. The draw back from Supreme Protector (UHMW-PE-512WE) is that there are no known adhesives that will stick. The method of connecting the material is by sewing, which will not keep MOSES watertight. A solution is to research methods of watertight sewing, i.e. with a gasket, or developing a new adhesive.

Table 7: Material Properties

Material	Tensile Strength (GPa)	Density (g/cm^3)	Elongation % (at break)	Str. Retention % (in 3.5% NaCl After 6 months)	Str. Retention % (due to UV rays after 6 Months)
Zylon AS	5.8	1.54	3.5	90	35
Zylon HM	5.8	1.56	2.5	N/A	35
p-Aramid	2.8	1.45	2.4	100	N/A
m-Aramid	0.65	1.38	22	N/A	N/A
Steel Fiber	2.8	7.8	1.4	N/A	N/A
HS-PE	3.5	0.97	3.5	N/A	N/A
PBI	0.4	1.4	30	N/A	N/A
Polyester	1.1	1.38	25	N/A	N/A
UHMW-PE-509WE	3.2	0.49	3	100	70
UHMW-PE-512WE	4	0.27	3	100	70
Kevlar 29	3.6	1.44	3.6	100	N/A
Kevlar 49	3.6	1.44	2.4	100	N/A

Deployment

In Water Roll Out

After the spool, on which MOSES is contained, has been set into the water, the air compressor and water pump will be attached. The recommended material and the roadway are positively buoyant so the MOSES spool will float along side the ship. Next the air compressor will be turned on to inflate the reservoir frame and this action will unroll the spool (Figure 15).

Figure 15: Deployment 1
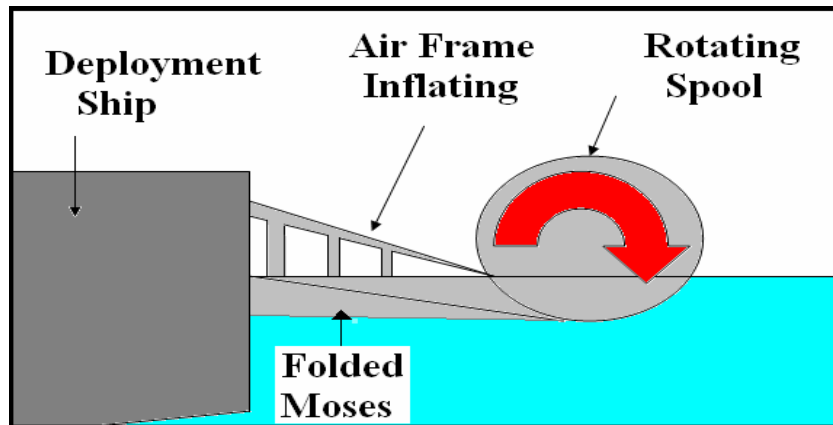
When the spool has completely unrolled and the airframe is filled to the proper pressure, the water pump will be turned on. The bag will be filled until proper height in the reservoir is reached (Figure 16).

Figure 16: Deployment 2
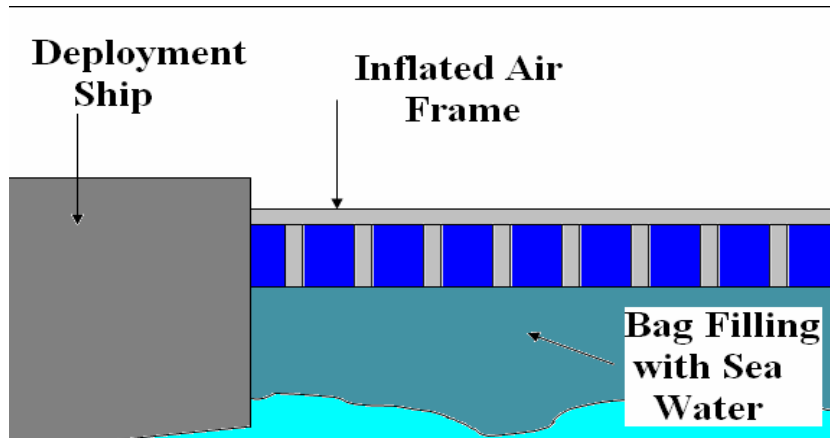
The next step is to detach both the air compressor and water pump from the system. Lastly the roadway will be laid if it wasn't already attached. The roadway will be in a like spool but rolled down the length of MOSES and attached using Velcro.

The explanation for the detachable roadway is that if it were damaged by tank treads, it can be easily mended or replaced. Also it will make the MOSES spool considerably smaller in size, which is to great benefit on sea transport vessels.

Recovery

Removing the Roadway

Before the recovery process is started it must be decided whether or not to remove the roadway. There are many factors that go into this process. One factor is space constraints in the sea transport ship, if space is limited, then it would be advised to remove the road. The con to this decision is that it will take more time in general for recovery, and the next deployment.

If the decision is made to remove the roadway, the process is simple. Using the special Velcro release tool, pry the roadway at the shore side and roll toward the ship. Once the spool has reached the ship it will need to be secured and transported to its stowage area.

Recovery of MOSES

The process to recover MOSES is broken down into a few steps. First step is to run the lead cables from the two winches on board the ship to the beach end of MOSES and secure. Next step is to clear MOSES of any debris or personnel and open the release valve on the shipside. Once the valve is completely opened and the water above the water line has diminished, the winches will be turned on and will pull the beach end of MOSES towards the ship (Figure 17). This action will curl MOSES backwards, evacuate more seawater, and theoretically the winches will be pulling just the weight of the material and/or roadways thus not need extremely large winches.

Figure 17: Recovery 1
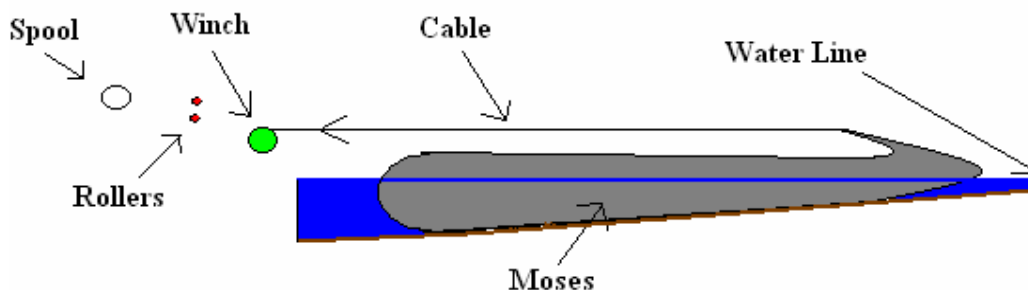
Once the beach end is pulled up to the ship, another lead line will be attached to the tip of MOSES and then fed through rollers into the Spooling mechanism. The purpose of the rollers is to evacuate more water and flatten MOSES to minimize its storage volume. The spooler will then roll MOSES up (Figure 18). Once completed the MOSES spool will be secured and transferred below deck to its designated stowage area.

Figure 18: Recovery 2
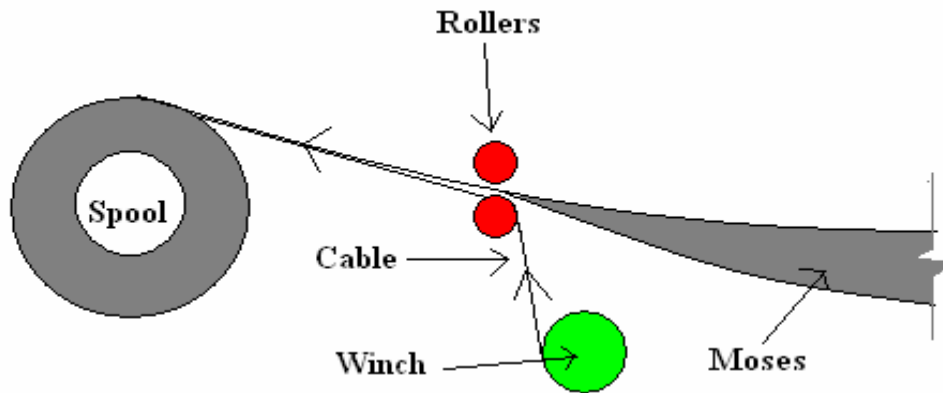
Mechanical Components

Air Compressor

The maximum pressure calculated to keep white water from washing over MOSES, hold up the reservoir, and to deploy MOSES were calculated to be 77.7 kPa (0.77atm). The total volume of the airframe to be filled was 7.07 m³. These volumes and air pressures are small so there are many air compressors available to accomplish this task. The decision will be based on time to inflate versus weight of compressor. Note it would be simpler and more convenient if the deployed ship's onboard air compressor could deploy and inflate the air frames.

Pump

The fire hose system on the deployment ship was considered to save the trouble and weight of stowing and using an outside pump, but quickly thrown out because the safety of the ship and crew are a priority. So a large pump that can make MOSES operational must be stowed on board the deployed ship. The maximum volume of the largest MOSES envisioned was 3,064 m³. Considering the large volume that needs to be filled, a high flow/low-pressure pump seemed to be the ideal option. A pump was found from Fisher Pumps that can yield an extremely high flow rate of 20,000 gal/min, which converts to 75.70 m³/min. This flow will fill and pressurize MOSES in approximately 40 minutes. This pump weighs approximately 4 tons, which is a substantial amount, but again it becomes a trade off for time versus weight.

Connections and Valves

The connections and valve that are needed for MOSES to operate are currently available. A suggested valve to be used is one made by Tyco. Tyco produces many sizes and shapes. A circular release valve was with a diameter of 76 cm (30 inches) was selected for the design. This valve, during recovery, has sufficient capacity to complete the task in an estimated three hours.

Connections to the MOSES will also need to be explored because the methods used in the model testing will not work on the full scale. The Supreme Protector material

recommended has problems with adhesives and the connections will need to be made with out them. The initial idea of using a male/female connection through the bag with rubber gaskets sealing it tight is a sound solution, but testing and perfecting this method with the actual material is necessary.

Laboratory Experiment

Experiments

There were three experiments that were conducted on a 1/20-scale model of MOSES. A pressure test, a deflection test, and a curvature test were conducted. The pressure test was conducted by adding weight to the already fully pressurized system while recording the increase of pressure. The deflection test was executed in the same way as the pressure test. Measurements of the deflection in the material were taken. Other observations were made during the experiments such as effects that waves had on the system, and whether the recovery plan was plausible.

Conclusion

Numerous conclusions can be drawn from the lab test and they show that the fundamental ideas behind the MOSES concept are reasonable. It was evident that:
when a weight is placed on a flexible membrane structure filled with water, there will be a very small increase in internal water pressure.
a pressurized water filled bag will be rigid and act as a stable platform and deform very little when loaded.
a fabric tube can be constructed in such a way that it can be inflated to take an irregular shape; and
this bag will be heavy enough that it will not be moved by ocean tides or waves.

Tests were performed to determine the pressure increase, and deflection caused by different combinations of surface loadings. The pressure results were useful because they validated the assumption that when a weight, small in proportion to the total system weight, is placed on the surface there will only be a small increase in the internal water pressure. This theory was supported by our experimental results. The estimated weight of water in the test above the water line was 175 kg. The data shows that even when 41 kg, 23% of the weight, is placed on the MOSES the pressure only increased 0.5 kPa (0.005 atm). Also the results from the pressure test show that induced pressures are in no way proportional to a surface loading contact pressure or the total loading dispersed over the water plane area of the bag. This is important because it shows that the internal pressures are very difficult to estimate. In order to better predict these pressures more tests and models should be prepared.

The deflection test was used to validate the claim that when an inelastic bag filled with pressurized water is loaded externally it will be extremely rigid and will not deflect. While it was difficult to fully test this claim because the fabric used for the construction of the test bag was not extremely inelastic the results did show that very small deflections could be expected. The deflection at a loading of 27.9 kg was around 2 cm. This is impressive considering the scale weight of a tank is only 8.8 kg. Another interesting observation is the linear trend of the deflection data. This is encouraging because this

might show that there is no phenomenon analogous to buckling for the MOSES system. This would make the system much safer because there may never be a condition where a slight increase in the loading will cause massive increases in deflections.

The curvature test allowed for a more accurate way to understand what the final shape of MOSES is likely to be. From the scale model, the average height from the top of the humps to the valley in the center was 1.5 cm. This is a little larger than expected, but is overly concerning. This problem could be easily corrected by adding more ribs or by making the center rib slightly longer then the outside ribs.

While it is difficult to take measurements on every feature of the MOSES system, especially since the actual materials were not used, some very encouraging observations were made. These observations give validity to some of the other theories behind the concept of MOSES. For the model, ribs were placed on the interior and ran the length of the bag. These ribs were attached to give the MOSES a more oval shaped cross section, and thus more stability. This was proven to be plausible by the shape that the model took after it was filled and pressurized.

Another observation that was made was that when the bag was filled it was nearly impossible to move it. This was a excellent finding because it gives validity to the argument that MOSES can stand up to Sea State 4 waves and currents. Also it was observed that when the front end was opened and the back was pulled out of the water to allow the system to drain, the bag was practically vacuum sealed shut after all of the water poured out. This is very interesting as far as the recovery of the bag is concerned because this shows that special equipment might not be needed to make sure the bag is compact for storage.

One observation that might lead to a redesigning of the reservoir system was the large fluctuations in the manometer tubes caused by swells hitting the bag. The raising and lowering of the water level could cause MOSES to be unstable and also to dump some of the water that is held in the reservoir. The fluctuations that were observed were around 2 to 3 cm and seem a bit concerning as the project moves forward. One possible solution to the problem could be placing one-way flap valves on the inlets from the reservoir to the main bag. This would allow water to drain into the bag but not out which theoretically would stop the large fluctuations.

Overall this experiment did a very good job at giving a more concrete understanding of how MOSES will react to loadings and function in a marine environment. The data from the experiments seem to be fairly precise with very little deviation from one trial to another. The accuracy of the results has yet to be determined due to a lack of similar tests performed.

Conclusions

The MOSES concept presented in this report is viable and was demonstrated in a successful scale model test. While the qualitative results proved promising, there still needs more research into the development of quantitative models to more precisely predict induced stresses, strains, and pressures.

Deployment and recovery of the system appears feasible but the control mechanisms for these operations require development. The MOSES system is novel because of its fabric material construction, which can be compacted, stowed and easily deployed. Compared to the current causeways, MOSES has advantages in terms of deployment/recovery times, stowage volumes, and overall weight. These attributes make the inflatable causeway appealing for the future development of this ship to shore transition technology.

Recommendations

The next step for the MOSES project is the development of more advanced project modeling and testing. Because this system is so innovative, there has not been much research besides what has been done here. The future of MOSES depends on the ability to predict the stresses in the bag when loaded. If that is accomplished it is recommended to look into cheaper and more workable materials. These materials will be weaker than those explored but this should not pose a problem as long as they maintain a high rigidity when pressurized.. The materials selected were chosen primarily to demonstrate that current materials are more than strong enough to cope with the stresses that the MOSES system would induce. Other areas for further research are configurations and mechanical components for both deployment and recovery.

One problem with the MOSES system as it stands now is that it is one single unit that can only be used on specific beach slopes. Further research into modularity should be conducted to make MOSES more versatile. A modular system could be custom built for each particular beach in terms of gradient and distance from ship to shore. Also MOSES would be less susceptible to catastrophic failure due to rips because only one module would deflate instead of the entire system. Then a working section could replace the specific section. Another area that was not fully explored in this report is the ship to MOSES transition. The idea of using a Roll-On / Roll-Off Discharge Facility or floating barge transformed into a jack up barge was postulated but needs further development.

Alternate Uses

MOSES is not limited to use as a causeway. It could be employed as a breakwater or as a jetty to help abate beach erosion. MOSES can be a used as a temporary causeway or pier for commercial use. This could be attractive to municipalities expecting large crowds at their waterfronts for holidays or other one-time events. Another use for MOSES is as a Dry Dock. A ship could be moved to position, and then the MOSES would inflate and raise the vessel above the water line. Also the presence of a large heavy barrier that can be rapidly constructed would be good for flood protection. It could be used in place of sandbags or to help shore up a levy.

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Appendix: Laboratory Report

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5 July 2007
MOSES 1/20 Scale Model Test
Laboratory Experiment #1

Objective:

To gain a better idea of how MOSES will react to loading and the validity of the assumptions that were made for the structural calculations. The tests performed were a load test, curvature test, and a deflection test.

Materials:

1/20 scale model of MOSES
3 Manometer Tubes 6ft in length
Manometer Stands
2 C-Clamps (large)
3 1"x 3"x4' wooden boards
2 Five-Gallon Buckets
2 9"x 11" x 1" Bucket Platform
2 12" Rulers
Plum Line
2 One Gallon Jugs

Procedure:

Setup:

Partially inflate MOSES by dragging it through the water with the open-end leading. Stop at desired location and Clamp the open end closed. Roll MOSES one revolution around one of the 1"x 3"x4' wooden boards. Next sandwich the roll with the other two 1"x 3"x4' wooden boards and then clamp tight.
Connect manometers to MOSES and to Stands. Use plum line on the stands to make sure that they are vertical.
Fill reservoir with the one-gallon jug until MOSES is completely filled and pressurized. This is accomplished when the water begins to rise in the manometer tubes and the reservoir.

Load Test:

Mark zeros on manometers
Place a five-gallon bucket and one 9"x 11" x 1" Bucket platform on the MOSES
Pour one gallon of water into bucket. Mark manometer reading
Repeat step three until five gallons are poured.
Once the 5 gallons have been poured and the manometer has been marked, empty the bucket.
(Note: when MOSES is clear of the bucket and platform, check to see if the manometers are still zeroed. If they are not, there may be a leak that will need to be repaired.)

Place 2 five-gallon buckets and two 9"x 11" x 1" Bucket platforms at a different spots on MOSES
Pour one gallon on each. Mark monometer heights.
Repeat step 7 until five gallons have been poured into each bucket.

Deflection Test:

Tape the 12" ruler to the top of the bucket platform.
Make sure the ruler extends to a manometer stand.
Place bucket on platform
Mark initial position of ruler.
Add one gallon of water
Mark height.
Repeat steps 5-6 until five gallons are reached.
Place other platform and bucket on top of filled bucket.
Add one gallon to top bucket.
Mark height.
Repeat steps 9-10 until five gallons are reached.

Curvature Test:

Place ruler across the ribs.
Use second ruler to record the distance from the central valley to the first ruler.
Take measurement every three feet along the length of MOSES.
Data:

Table 8: Load Test Raw Data (One Bucket)

Manometer A

loading (gal)	loading (kg)	pressure head (cm)	pressure (kPa)	pressure (atm)
1	5.16	0.6	0.06	0.00058
2	8.95	1.25	0.12	0.0012
3	12.75	1.45	0.14	0.0014
4	16.54	2.2	0.21	0.0021
5	20.34	2.6	0.26	0.0025

Manometer B

loading (gal)	loading (kg)	pressure head (cm)	pressure (kPa)	pressure (atm)
1	5.16	0.7	0.069	0.0007
2	8.95	1.2	0.12	0.0012
3	12.75	1.65	0.162	0.0016
4	16.54	2.25	0.22	0.0022
5	20.34	2.85	0.28	0.0028

Manometer C

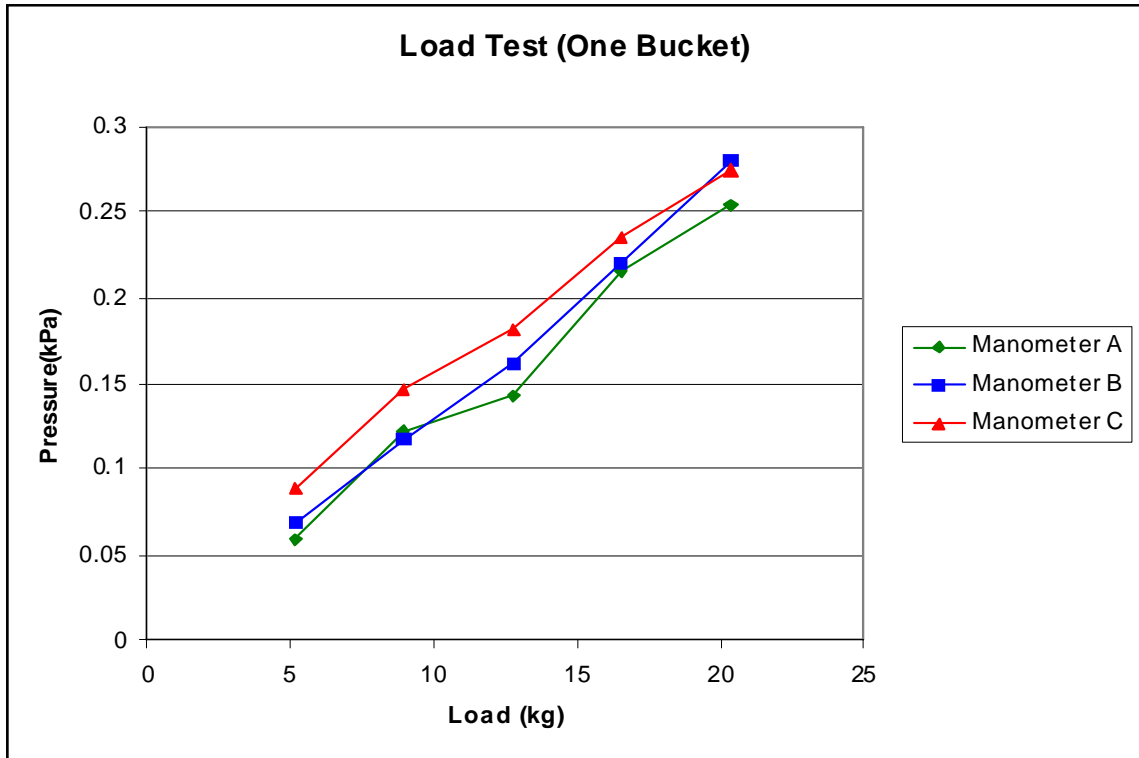| loading (gal)	loading (kg)	pressure head (cm)	pressure (kPa)	pressure (atm)
1	5.16	0.9	0.09	0.0009
2	8.95	1.5	0.15	0.0015
3	12.75	1.85	0.18	0.0018
4	16.54	2.4	0.23	0.0023
5	20.34	2.8	0.27	0.0027

Figure 19: Load Test (One Bucket)

Table 9: Load Test Raw Data (Two Buckets)

Manometer A

Loading (gal)	Loading (kg)	Pressure head (cm)	Pressure (kPa)	Pressure (atm)
2	10.31	1.15	0.11	0.0011
4	17.90	2.15	0.21	0.0020
6	25.50	2.9	0.28	0.0028
8	33.09	3.9	0.38	0.0037
10	40.68	4.9	0.48	0.0047

Manometer B

Loading (gal)	Loading (kg)	Pressure head (cm)	Pressure (kPa)	Pressure (atm)
2	10.31	1.15	0.11	0.0011
4	17.90	1.85	0.18	0.0018
6	25.50	2.8	0.27	0.0027
8	33.09	3.65	0.35	0.0035
10	40.68	4.7	0.46	0.0045

Manometer C

Loading (gal)	Loading (kg)	Pressure head (cm)	Pressure (kPa)	Pressure (atm)
2	10.31	1.05	0.10	0.0010
4	17.90	1.9	0.18	0.0018
6	25.50	3	0.29	0.0029
8	33.09	3.9	0.38	0.0038
10	40.68	4.85	0.47	0.0047

Figure 20: Load Test (Two Buckets)
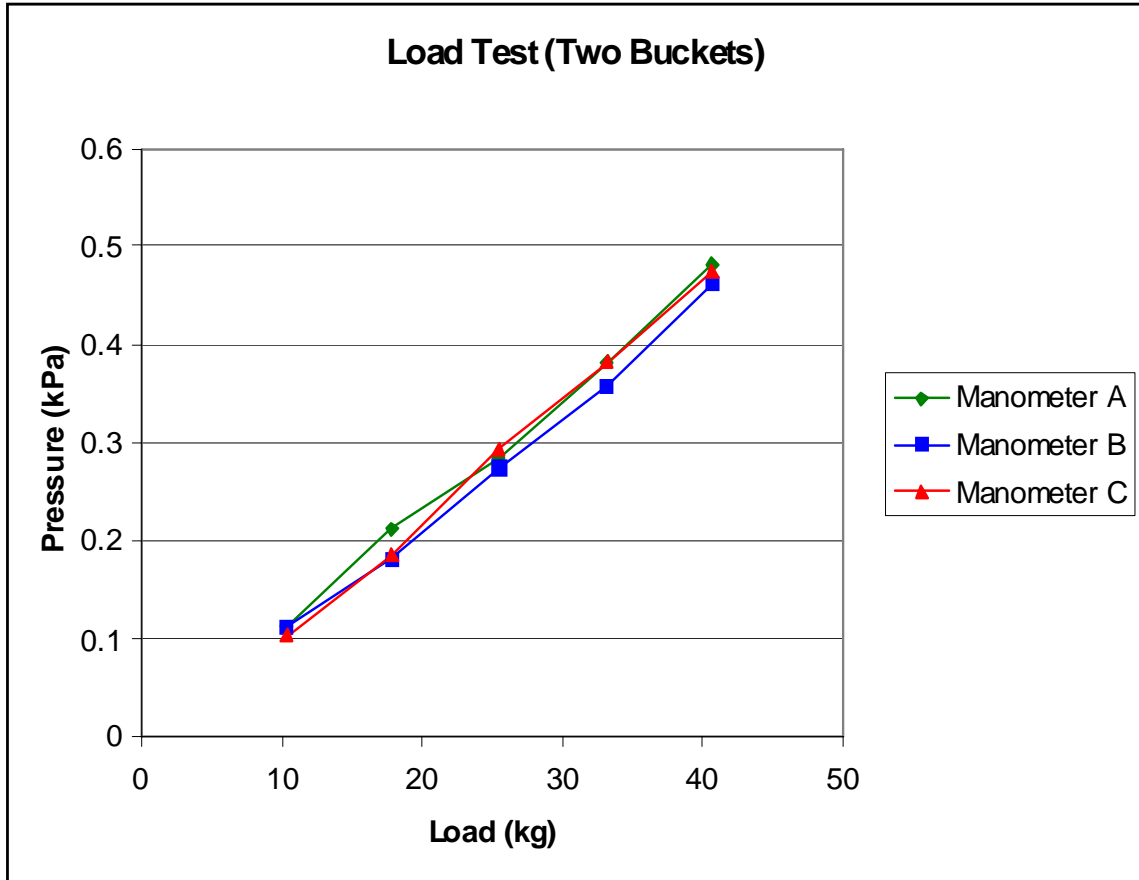
Table 10: Deflection Data

loading (gal)	loading (lbs)	loading (kg)	Trial 1 (cm)	Trial 2 (cm)	Trial 3 (cm)
1	11.35	5.15	0.2	0.15	0.2
2	19.7	8.95	0.4	0.45	0.4
3	28.05	12.75	0.6	0.65	0.6
4	36.4	16.54	1.15	1	1
5	44.75	20.34	1.5	1.35	1.35
6	53.1	24.13	1.7	1.65	1.75
7	61.45	27.93	2.1	1.95	2

Figure 21: Deflection
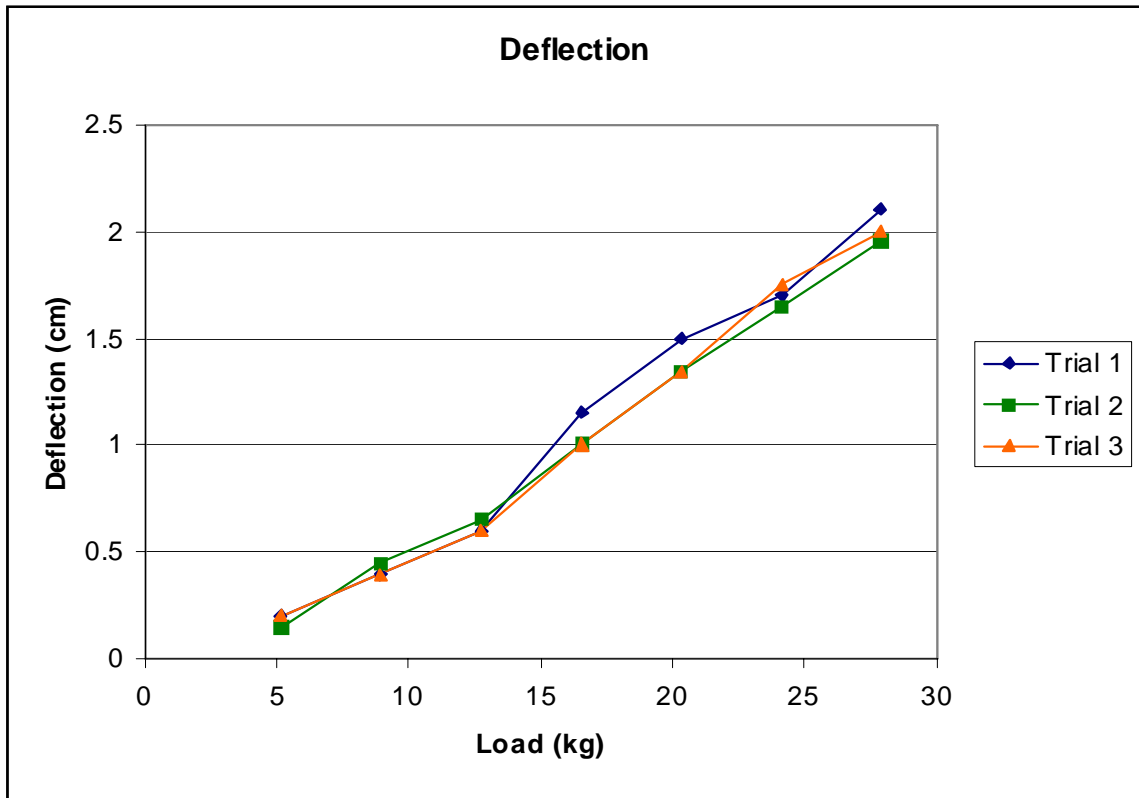
Table 11: Curvature Data

Length Along MOSES (m)	depth (cm)
1	1.55
2	1.6
3	1.45
4	1.55

31

Results:

Water Plane Length: 4.32m
Water Plane Width: 42 cm
Water Plane Area: 1.81 m^2
Bucket Platform Length: 28 cm
Bucket Platform Width: 23 cm
Bucket Platform Area: 0.06 m^2

Table 12: Theory vs. Experimental (One Bucket)

loading (kg)	water plane (m^2)	pressure (kPa)	foot print (m^2)	pressure (kPa)	manometer (kPa)
					A
5.16	1.81	0.03	0.06	0.79	0.06
8.95	1.81	0.05	0.06	1.36	0.12
12.75	1.81	0.07	0.06	1.94	0.14
16.55	1.81	0.09	0.06	2.52	0.22
20.34	1.81	0.11	0.06	3.10	0.26
					B
5.16	1.81	0.03	0.06	0.79	0.07
8.95	1.81	0.05	0.06	1.36	0.12
12.75	1.81	0.07	0.06	1.94	0.16
16.55	1.81	0.09	0.06	2.52	0.22
20.34	1.81	0.11	0.06	3.10	0.28
					C
5.16	1.81	0.03	0.06	0.79	0.09
8.95	1.81	0.05	0.06	1.36	0.15
12.75	1.81	0.07	0.06	1.94	0.18
16.55	1.81	0.09	0.06	2.52	0.24
20.34	1.81	0.11	0.06	3.10	0.27

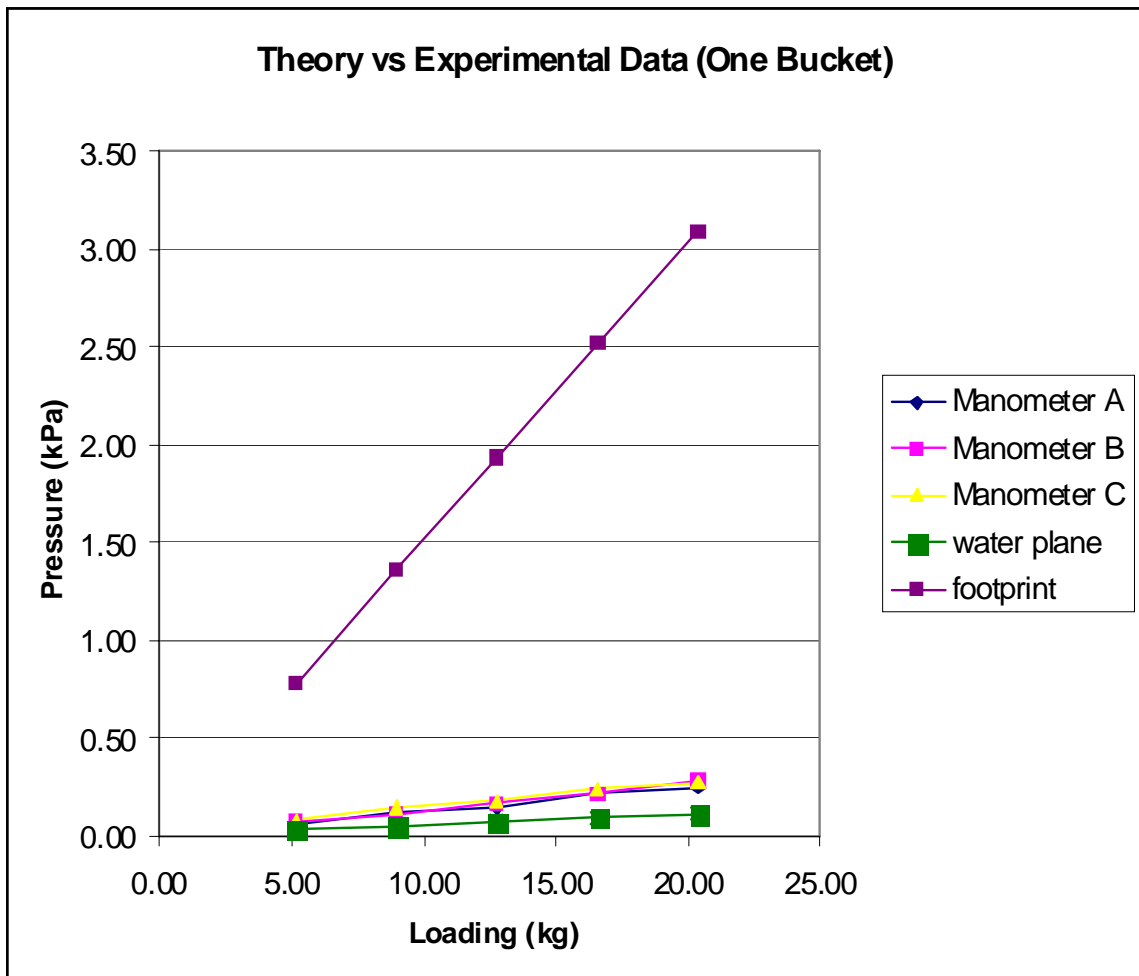**Figure 22: Theory vs. Experimental Data (One Bucket)**

Table 13: Theory vs. Experimental (Two Buckets)

loading (kg)	water plane (m^2)	pressure (kPa)	foot print (m^2)	pressure (kPa)	manometer (kPa)
					A
10.32	1.81	0.06	0.13	0.79	0.11
17.91	1.81	0.10	0.13	1.36	0.21
25.50	1.81	0.14	0.13	1.94	0.28
33.09	1.81	0.18	0.13	2.52	0.38
40.68	1.81	0.22	0.13	3.10	0.48
					B
10.32	1.81	0.06	0.13	0.79	0.11
17.91	1.81	0.10	0.13	1.36	0.18
25.50	1.81	0.14	0.13	1.94	0.27
33.09	1.81	0.18	0.13	2.52	0.36
40.68	1.81	0.22	0.13	3.10	0.46
					C
10.32	1.81	0.06	0.13	0.79	0.10
17.91	1.81	0.10	0.13	1.36	0.19
25.50	1.81	0.14	0.13	1.94	0.29
33.09	1.81	0.18	0.13	2.52	0.38
40.68	1.81	0.22	0.13	3.10	0.48

Figure 23: Theory vs. Experimental Data (Two Buckets)
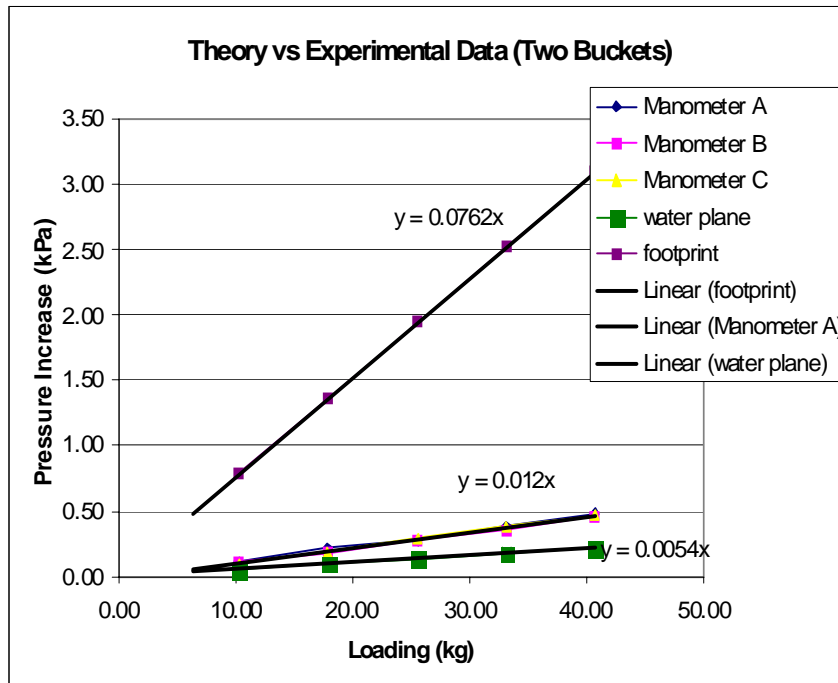
Conclusion:

Numerous conclusions can be drawn from this lab test and they show that the root ideas behind the concept of the MOSES project are reasonable. These ideas include the theory that if a weight is placed on the surface of a water filled structure there will be a very small increase in internal water pressure. Also a pressurized water filled bag will be rigid and act as a stable platform and deform very little when loaded. Another idea is that a fabric tube can be constructed in such a way that it can be inflated to take an irregular shape. Also this bag will be heavy enough that it will not be moved by ocean tides or sea state 4 waves.

Tests were performed to determine the pressure increase, and deflection caused by different combinations of surface loadings. The pressure results were useful because they validated the assumption that when a weight, small in proportion to the total system weight, is placed on the surface there will only be a small increase in the internal water pressure. This theory was supported by our experimental results. The estimated weight of water above the water line was 175 kg. Our data shows that even when 41 kg, 23% of the weight, is placed on the MOSES the pressure only raised 0.5 kPa (0.005 atm). Also the results from the pressure test show that induced pressures are in no way proportional to a surface loadings contact pressure or the total loading dispersed over the water plane area of the bag. This is important because it shows that the internal pressures are very difficult to estimate. In order to better predict these pressures more tests and models should be prepared.

Another test that was performed was a test to determine the deflection of the bag while being loaded. This test was used to validate the claim that if an inelastic bag is filled with pressurized water then it will be extremely rigid and will not deflect. While it was tough to test this claim because the fabric used for the construction of the bag was not extremely inelastic the results did prove that very small deflections can be expected. The deflection at a loading of 27.9 kg was right around 2 cm. This is impressive considering the scale weight of a tank is only 8.8 kg. Another interesting observation is the linear trend of the deflection data. This is encouraging because this might show that there is no phenomenon analogous to buckling for the MOSES system. This would make the system much safer because there may never be a condition where a slight increase in the loading will cause massive increases in deflections.

The curvature test allowed for a more accurate way to understand what the final shape of MOSES is likely to be. From the scale model we recorded an average height from the top of the humps to the valley in the center to be 1.5 cm. This is a little larger than we would have liked to see, but is not too big of a concern. Also this problem could be easily corrected by adding more ribs or by making the center rib slightly longer then the outside ribs.

While it is difficult to take data on every aspect of the MOSES system, especially when the actual materials are not being used, some very encouraging observations were made. These observations give validity to some of the other theories behind the concept of MOSES. One idea was that it would be possible to construct a fabric bag in such a way that it could be inflated into an irregular shape. For the model, ribs were placed on the interior and ran the length of the bag. These ribs were attached in order to give the

MOSES a more oval shaped cross section, and thus more stability. This was proven to be plausible by the shape that the model took after it was filled and pressurized. Another observation that was made was that when the bag was filled it was nearly impossible to move it. This was a good finding because it gives validity to the argument that MOSES can stand up to Sea State 4 waves and currents. Also we observed that when the front end was opened and the back was pulled out of the water to allow the system to drain, the bag was practically vacuum sealed shut after all of the water poured out. This is very interesting as far as the recovery of the bag is concerned because this shows that special equipment might not be needed to make sure the bag is compact for storage. One observation that might lead to a redesigning of the reservoir system was the large fluctuations in the manometer tubes caused by swells hitting the bag. The raising and lowering of the water level could cause MOSES to be unstable and also to dump some of the water that is held in the reservoir. The fluctuations that were observed were around 2 to 3 cm and seem a bit concerning as the project moves forward. One possible solution to the problem could be placing one-way flap valves on the inlets from the reservoir to the main bag. This would allow water to drain into the bag but not out which theoretically would stop the large fluctuations.

Overall this experiment did a very good job at giving a more concrete understanding of how MOSES will react to loadings and function in a marine environment. The data from the experiments seem to be fairly precise with very little deviation from one trial to another. The accuracy of the results has yet to be determined due to a lack of similar tests performed.

Figure 24: Scale Model Causeway

Figure 25: Experiment Setup – Two Buckets

Figure 26: Experimental Causeway Supporting Intern